

Limits on R -parity violation from cosmic ray antiprotons

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We constrain the hadronic R -parity violating couplings in extensions to the minimal supersymmetric standard model. These interactions violate baryon and lepton number, and allow the lightest superpartner (LSP) to decay into standard model particles. The observed flux of cosmic ray antiprotons places a strong bound on the lifetime of the LSP in models where the lifetime is longer than the age of the universe. We exclude $10^{-18} \leq |\lambda''| \leq 10^{-15}$ and $2 \times 10^{-18} \leq |\lambda'| \leq 2 \times 10^{-15}$ except in the case of a top quark, where we can only exclude $4 \times 10^{-19} \leq |\lambda'| \leq 4 \times 10^{-16}$. [S0556-2821(98)02912-9]

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I. INTRODUCTION

In supersymmetric models, gauge invariance allows interactions that violate lepton- or baryon-number conservation. To avoid them, a discrete symmetry called R -parity is often imposed. The R -parity of a particle is defined as $R = (-1)^{2S+L+3B}$, where S is its spin, and L and B are its lepton and baryon numbers. R is $+1$ for all standard model particles and -1 for all superparticles. Alternatively, it is an interesting exercise to allow R -parity violating couplings and constrain them by experimental observations or cosmological considerations. With R -parity violation, the lightest superpartner decays into standard model particles. We will assume that the lightest superpartner is the neutralino.

Antiprotons are a rare component of cosmic rays, most probably produced in spallation reactions in the interstellar medium. The measured antiproton flux limits any additional antiproton production in the galaxy. We find a powerful bound on the lifetime of the lightest superpartner from the observed flux of cosmic ray antiprotons. This allows us to bound the R -parity violating interactions that appear in extensions to the minimal supersymmetric standard model.

We find the relic density of the lightest superpartner (LSP) using the standard cosmological model. We then allow these particles to decay via the hadronic R -parity violating operators. We employ simple models for the production rate and the propagation of the antiprotons. We can limit the R -parity violating couplings with observations of the antiproton spectrum in cosmic rays.

Our results strictly apply when the lifetime of the neutralino is longer than the age of the universe. However, there are other cosmological limits based on nucleosynthesis in the early universe, recent structure formation, diffuse photon and neutrino fluxes, and spectral distortions in the cosmic microwave background that cover a large fraction of neutralino

lifetimes shorter than the age of the universe, and may well completely close the gap between this result and laboratory constraints.

II. SUPERSYMMETRIC MODEL

The supersymmetric model we consider is a minimal extension of the standard model with explicit R -parity breaking, defined by the superpotential

$$W = -h_e^{ij} E_i^c L_j H_1 - h_d^{ij} D_i^c Q_j H_1 + h_u^{ij} U_i^c Q_j H_2 - \mu H_1 H_2 \\ + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c. \quad (1)$$

i, j, k are generation indices; L_i and Q_i are the $SU(2)$ -doublet lepton and quark superfields; E_i^c , U_i^c and D_i^c are the singlet superfields; and H_1 and H_2 are the doublet Higgs superfields. h_e^{ij} , h_d^{ij} and h_u^{ij} are Yukawa matrices, and μ is a free parameter [1].

The last two terms in the superpotential violate lepton- and baryon-number conservation explicitly. For three generations, there are 27 λ' couplings and 9 λ'' couplings, since λ''_{ijk} is antisymmetric under exchange of the last two indices.

Supersymmetry is broken softly by a scalar potential that in general contains many unmeasured parameters. For our purposes, a simple parametrization suffices. We assign a common mass scale m_0 to the sleptons and squarks at the electroweak scale, we relate the gaugino mass parameters M_1, M_2, M_3 by means of grand unified theory (GUT) relations, and we keep the trilinear soft terms A_t and A_b only for stop and sbottom. Electroweak symmetry is broken at tree level by assigning vacuum expectation values v_1 and v_2 to the neutral scalar components of H_1 and H_2 . The ratio $\tan \beta = v_2/v_1$ and the pseudoscalar Higgs boson mass m_A remain as free parameters. The total number of parameters is therefore seven. Further details on the class of models we consider are given by Bergström and Gondolo [2].

We use the scans of supersymmetric parameter space in Bergström, Edsjö, and Gondolo [3]. They consist of $\sim 10^4$ models that satisfy the experimental constraints reported by

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the Particle Data Group [4], plus the bounds on the Higgs sector and chargino masses from the CERN e^+e^- collider LEP (we update to LEP2W [5]) and the constraints on the $b \rightarrow s\gamma$ rate from CLEO [6]. The scans span values of $|\mu|$ and $|M_2|$ up to 5 TeV, of m_0 up to 3 TeV, of $|A_t|$ and $|A_b|$ up to $3m_0$, of m_A up to 1 TeV, and of $\tan\beta$ between 1 and 50. This range extends even beyond the parameter region usually considered as plausible.

III. COMPOSITION OF THE GALACTIC HALO

We do not assume that the dark matter is supersymmetric in nature. Given a supersymmetric model, the relic density of neutralinos is fixed and calculable in the standard cosmological model. We use the relic density computed by Edsjö and Gondolo [7], who include all neutralino self-annihilation diagrams, resonance and threshold effects, and chargino-neutralino coannihilations. In every model that is cosmologically allowed, the lightest neutralino is a cold relic from the big bang. Being a cold relic, we expect that it is attracted into the gravitational potentials of galaxies, and is at present a component of the cold dark halo.

We use the simple estimate that the dark matter density of the galactic halo at the position of the solar system is 0.3 GeV cm^{-3} . Neutralinos may make up the entire halo or only some fraction f . This fraction $f \geq \Omega_\chi / \Omega_{\text{DM}}$, where Ω_A is the cosmological density of species A measured in units of the critical density.

We now need an estimate of Ω_{DM} . A common prescription [8] is to take $\Omega_{\text{DM}} = \Omega_\chi$ if $\Omega_\chi h^2 \geq 0.025$, which is the value indicated by dynamical mass measurements of the amount of dark matter in galactic halos. If $\Omega_\chi h^2 \leq 0.025$, this prescription sets $\Omega_{\text{DM}} h^2 = 0.025$. This procedure is not conservative enough for our purposes because there may be more than one cold dark matter component in the galactic halo. Therefore, we use the constraint that $\Omega_{\text{DM}} h^2 < 1$, based on the age of the universe [8], to give a lower bound on $f = \Omega_\chi h^2$. In this way we obtain a conservative limit on the R -parity violating couplings. This may be overly conservative, and indeed our final results would improve by approximately a factor of five if we used the less conservative fraction.

IV. DECAY RATE

We consider neutralino decay through both the lepton-number violating term $\lambda' L Q D^c$ and the baryon-number violating term $\lambda'' U^c D^c D^c$ in the superpotential. The coupling λ'_{ijk} gives rise to the decays $\chi \rightarrow \nu_i d_j \bar{d}_k, \chi \rightarrow e_i^- u_j \bar{d}_k$ and their charge conjugates. The coupling λ''_{ijk} gives rise to the decays $\chi \rightarrow u_i d_j d_k$ ($j \neq k$) and their charge conjugates.

The differential decay rates for these processes are calculated in Ref. [9]. Here we quote the decay rate for $\chi \rightarrow uds$ in the limit where the squarks are heavy and degenerate:

$$\Gamma(\chi \rightarrow uds) = \frac{3}{32\pi^3} m_\chi |\lambda''_{112}|^2 g^2 \left(\frac{m_\chi}{m_{\tilde{q}}} \right)^4 \left[2 \tan^2 \theta_W |N_{\chi 1}|^2 + \frac{m_u^2 |N_{\chi 4}|^2}{2m_W^2 \sin^2 \beta} + \frac{(m_d^2 + m_s^2) |N_{\chi 3}|^2}{2m_W^2 \cos^2 \beta} \right], \quad (2)$$

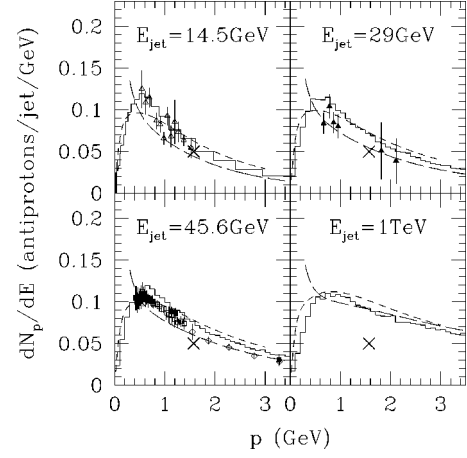


FIG. 1. Antiproton spectra in quark jets from theoretical predictions and e^+e^- annihilation data. Short- and long-dashed curves are the low-energy and the limiting MLLA spectra, histograms are obtained with the Lund Monte-Carlo program. Data points are from TPC (14.5 GeV), TOPAZ (29 GeV), ALEPH (41.6 GeV, full squares), DELPHI (41.6 GeV, diamonds) and OPAL (41.6 GeV, open squares). The cross indicates our choice of $dN_{\bar{p}}/dE$ at $p = 1.573 \text{ GeV}$.

where g is the $SU(2)_L$ coupling constant, $m_{\tilde{q}}$ is the degenerate squark mass, and $N_{\chi i}$ is the projection of the lightest neutralino on the interaction eigenstates $\tilde{b}, \tilde{w}^0, \tilde{h}_1$, and \tilde{h}_2 . When the gaugino fraction approaches unity, we see that the decay rate is

$$\Gamma = \frac{3}{16\pi^3} m_\chi |\lambda''_{112}|^2 g^2 \tan^2 \theta_W \left(\frac{m_\chi}{m_{\tilde{q}}} \right)^4. \quad (3)$$

When the gaugino fraction approaches zero, there is an additional suppression from the light quark masses,

$$\Gamma = \frac{3}{128\pi^3} m_\chi |\lambda''_{112}|^2 g^2 \left(\frac{m_\chi}{m_{\tilde{q}}} \right)^4 \left[\frac{m_u^2}{m_W^2 \sin^2 \beta} + \frac{m_d^2 + m_s^2}{m_W^2 \cos^2 \beta} \right]. \quad (4)$$

V. ANTIPROTON PRODUCTION

Antiprotons are produced in the jets formed by the final state quarks. We are interested in the energy spectrum of antiprotons $dN_{\bar{p}}/dE$ at energies of a few GeV.

It is quite difficult to calculate the spectrum $dN_{\bar{p}}/dE$, especially at low antiproton energies. There are basically two theoretical frameworks available: a perturbative QCD approach and the Lund Monte Carlo program. In Fig. 1 we compare the theoretical curves with the measured proton spectra per quark jet in e^+e^- annihilations at various jet energies (14.5 GeV [10], 29 GeV [11], and 45.6 GeV [12]) and also show the theoretical predictions at 1 TeV, one of the highest energies we need.

In the perturbative QCD approach, Dokshitzer *et al.* [13] provide a formalism for calculating hadron spectra from parton spectra in the modified double-logarithmic approximation (MLLA). The full MLLA formula for inclusive particle production is too difficult to evaluate, and no numerical expression is available. It has been shown that the simpler lim-

iting spectrum reproduces the total charged particle spectrum quite well [14]. However, as can be seen in Fig. 1, neither the limiting spectrum (long-dashed curves [13]) nor the low energy limit of the full MLLA spectrum (short-dashed curves [14]) fit data for protons in a satisfactory manner. As a theoretical alternative to the MLLA formalism, the Lund Monte Carlo [15] has been used by several authors, most recently by Bottino *et al.* [16]. However, it also does not match the data for protons satisfactorily (histograms in Fig. 1).

Inspecting the experimental data and the results of the Lund Monte Carlo program, we observe that the (anti)proton production rate in the high-energy tail of the spectrum increases with jet energy. This is verified in the data for charged particle production in jets and is a generic prediction of the MLLA formalism [13,14].

Based on these arguments, we decide to take the value $dN_{\bar{p}}/dE = 0.05$ antiprotons/jet/GeV at the momentum $p = 1.573$ GeV in which we want the antiproton spectra (see Sec. VII). This underestimates the production rate of antiprotons, and gives a conservative bound on the R -parity violating couplings.

The number of jets per decay N_{jets} is equal to the number of final state quarks, except when there is a top quark. The top decays before it can hadronize. We approximate the process $t \rightarrow W^+ b$ using the fact that the low energy proton spectrum is insensitive to the jet energy. The bottom quark forms a jet. In addition, we take the hadronic branching fraction of the $W, B (W \rightarrow \text{hadrons}) = 0.679$, as the probability to form two additional jets in the decay $W^+ \rightarrow u\bar{d}$ and its charge conjugate. The final values for N_{jets} are 3 for a $U^c D^c D^c$ decay without top, 4.358 for a $U^c D^c D^c$ with top, 2 for an LQD^c without top and 3.358 for an LQD^c with top.

We now obtain the volume production rate of antiprotons by multiplying the flat antiproton spectrum by the number density of neutralinos ρ_χ/m_χ and the number of jets per decay N_{jets} , and dividing by the lifetime $\tau_\chi = 1/\Gamma$,

$$\frac{dQ_{\bar{p}}}{dE} = \frac{dN_{\bar{p}}}{dE} \frac{\rho_\chi}{m_\chi} \frac{N_{\text{jets}}}{\tau_\chi}. \quad (5)$$

VI. ANTIPROTON PROPAGATION IN THE GALAXY

We use the diffusion model of Webber *et al.* [17] as implemented by Chardonnet *et al.* [18] to describe diffusion of antiprotons through the galaxy. The flux of antiprotons at the outer solar system is approximated by multiplying the source spectrum by the antiproton velocity and an appropriate diffusion time. The diffusion constant in the galaxy depends on the rigidity p of the particle and can be approximated by the following expression:

$$K = 6 \times 10^{27} \left(1 + \frac{p}{3Z \text{ GV}} \right)^{0.6} \text{ cm}^2 \text{ sec}^{-1}. \quad (6)$$

The region of turbulent magnetic fields responsible for diffusion can be approximated as a cylinder about 20 kpc in radius and 2 kpc high. This gives a diffusion time for antiprotons of

$$t_d = 6 \times 10^{15} \left(1 + \frac{p}{3 \text{ GV}} \right)^{-0.6} \text{ sec}. \quad (7)$$

The flux at the outer solar system beyond the influence of the solar wind is now given by

$$\Phi_{\bar{p}} = \frac{1}{4\pi} \frac{dQ_{\bar{p}}}{dE} v_{\bar{p}} t_d. \quad (8)$$

This flux is in units of antiprotons $\text{s}^{-1} \text{ cm}^{-2} \text{ GeV}^{-1} \text{ sr}^{-1}$.

The low energy spectrum is affected by the solar wind. We use a simple model to account for this [19]. The observed antiproton energy E and momentum k are given in terms of the initial energy outside the solar system $E_{\bar{p}}^-$:

$$E_{\bar{p}}^- = k_c \ln \frac{k+E}{k_c+E_c} + E_c + \Delta E, \quad k < k_c, \\ E_{\bar{p}}^- = E + \Delta E, \quad k \geq k_c. \quad (9)$$

We adopt values of the critical momentum k_c and energy shift ΔE that correspond to the period of minimum activity in the 11 year solar cycle, $k_c = 1.105$ GeV and $\Delta E = 495$ MeV. This gives the highest inner solar system flux, thus the conservative bound on the couplings.

The solar modulated flux is now given by

$$\Phi_{\bar{p}}(E) = \frac{E^2 - m_p^2}{E_{\bar{p}}^2 - m_p^2} \Phi_{\bar{p}}(E_{\bar{p}}^-). \quad (10)$$

VII. RESULTS

We proceed as follows. We choose a data point for the \bar{p} flux at the earth [20]. These data have large error bars, but will improve with the next generation of experiments to be done in space [21]. According to the data from BESS, at an energy of 1.4 GeV the antiproton flux at the top of the atmosphere is $6.4 \times 10^{-7} [\text{cm}^2 \text{ s sr GeV}]^{-1}$. We denote this flux as $\Phi_{\text{obs}}(E)$. From the values of the observed energy E and momentum k , we determine the unmodulated \bar{p} energy $E_{\bar{p}}^-$. This is the energy at which we evaluate the diffusion time t_d and the velocity v .

We now insist that the flux of antiprotons from neutralino decays be less than the observed flux. Including corrections due to solar modulation, the statement is

$$\frac{v_{\bar{p}} t_d}{4\pi} \frac{\rho_\chi}{m_\chi} \frac{N_{\text{jets}}}{\tau_\chi} \frac{dN_{\bar{p}}}{dE} \frac{E^2 - m_p^2}{E_{\bar{p}}^2 - m_p^2} < \Phi_{\text{obs}}(E). \quad (11)$$

We choose not to make a correction for the spallation production of antiprotons. The data are consistent with the picture that all cosmic ray antiprotons are made in spallation reactions, but there are a lot of uncertainties. There is no good model for the amount we should subtract, and we have chosen to ignore it. We thus obtain a conservative bound on the couplings.

Using the data we have chosen, we obtain a model independent bound on the lifetime of a hadronically decaying relic with mass $m_\chi \geq 10$ GeV

$$\tau_\chi \gtrsim \tau_\chi^{\bar{p}} = 7.9 \times 10^{28} \frac{N_{\text{jets}} f_\chi}{m_\chi / \text{GeV}} \text{ sec}, \quad (12)$$

where we choose the mass fraction of neutralinos in the galactic dark halo as $f_\chi = \Omega_\chi h^2$. Since we assume that the neutralino is in the galactic halo at present, this bound applies for lifetimes longer than the age of the universe t_0 . In other words, we can exclude lifetimes in the range $t_0 \leq \tau_\chi \leq \tau_\chi^p$ provided $t_0 \leq \tau_\chi^p$.

For these long lifetimes, our bounds are in general better than those from diffuse photons [22], $\tau_\chi \gtrsim 7 \times 10^{25} \text{ s } N_{\text{jets}} \Omega_\chi h^2$, and diffuse neutrinos [23], $\tau_\chi \gtrsim 10^{25} \text{ s } (m_\chi / \text{GeV})^{1.7} f_\chi$, except for some supersymmetric models with neutralino masses in the TeV range.

We can limit each element of the two coupling matrices λ' and λ'' separately, by choosing the coupling such that all of the measured \bar{p} flux comes from the neutralino decay via a single channel. Our excluded range of lifetimes then translates into the following *excluded* range of λ :

$$\lambda_{\bar{p}} \leq |\lambda| \leq \lambda_0, \quad (13)$$

where

$$\lambda_{\bar{p}} \approx 3.48 \times 10^{-15} \sqrt{\frac{m_\chi \tilde{\tau}}{N_{\text{jets}} f_\chi}} \quad (14)$$

is the upper limit on λ coming from the antiproton flux and

$$\lambda_0 \approx 1.8 \times 10^{-9} \sqrt{\tilde{\tau}} \quad (15)$$

is the value of λ for which the neutralino lifetime equals the age of the universe, which sets the validity of our analysis. In the previous formulas, m_χ is in GeV, $\tilde{\tau} = |\lambda|^2 \tau_\chi$ is in seconds, and the age of the universe is taken to be 10^{10} yr.

For virtually all models we find that $\lambda_{\bar{p}}$ is smaller than λ_0 by at least three orders of magnitude. Conservatively taking $N_{\text{jets}} = 2$ we find for the excluded range that

$$\frac{\lambda_0}{\lambda_{\bar{p}}} = 7.3 \times 10^5 \sqrt{\frac{\Omega_\chi h^2}{m_\chi / \text{GeV}}} \gtrsim 600. \quad (16)$$

If we would further demand that the neutralino be cosmologically interesting, namely $\Omega_\chi h^2 > 0.025$, we would expand the excluded range to $\lambda_0 / \lambda_{\bar{p}} \gtrsim 4000$.

We have plotted the upper bound on λ''_{112} as a function of the neutralino mass for 10^4 supersymmetric models in Fig. 2. The results are similar for all generations in the R -parity violating couplings, except for λ''_{3jk} which shows the top quark threshold (see Fig. 3). When the neutralino is lighter than the top quark, there is no bound on λ''_{3jk} at tree level. A bound can however be found at the one loop level [24].

In our sample of supersymmetric models, we find the absolute upper limits

$$|\lambda'_{ijk}|_{\bar{p}} \lesssim 2 \times 10^{-18} \quad (i, j, k \neq 3), \quad (17)$$

$$|\lambda'_{3jk}|_{\bar{p}} \lesssim 1 \times 10^{-18} \quad (j, k \neq 3), \quad (18)$$

$$|\lambda'_{i3k}|_{\bar{p}} \lesssim 4 \times 10^{-19} \quad (k \neq 3), \quad (19)$$

$$|\lambda'_{i33}|_{\bar{p}} \lesssim 3 \times 10^{-19}, \quad (20)$$

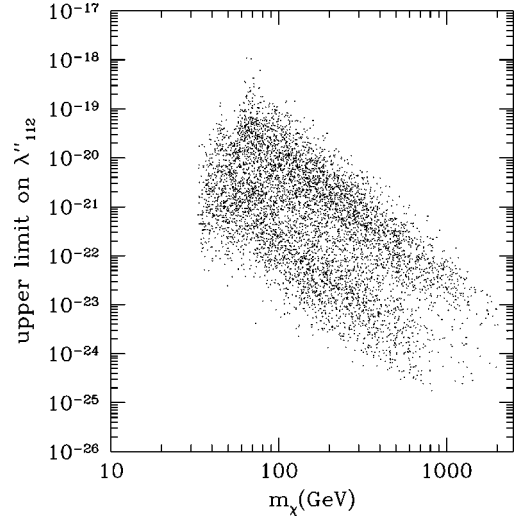


FIG. 2. Bounds on λ''_{112} from cosmic ray antiprotons as a function of neutralino mass for 10^4 SUSY models. The scatter plots for λ''_{ijk} are similar when $i \neq 3$. The scatter plots for λ'_{ijk} are also similar.

$$|\lambda''_{ijk}|_{\bar{p}} \lesssim 1 \times 10^{-18} \quad (i, k \neq 3), \quad (21)$$

$$|\lambda''_{ij3}|_{\bar{p}} \lesssim 1 \times 10^{-19} \quad (i \neq 3). \quad (22)$$

The apparent absence of an absolute upper bound on λ''_{3ij} is due to our neglect of one-loop diagrams. These upper limits depend on the neutralino mass, and improve considerably with higher masses. We find the following power law fits:

$$|\lambda'_{ijk}|_{\bar{p}} \lesssim 6 \times 10^{-22} (m_\chi / \text{TeV})^{-3.1} \quad (i, j, k \neq 3), \quad (23)$$

$$|\lambda'_{3jk}|_{\bar{p}} \lesssim 3 \times 10^{-22} (m_\chi / \text{TeV})^{-3.1} \quad (j, k \neq 3), \quad (24)$$

$$|\lambda'_{i3k}|_{\bar{p}} \lesssim 8 \times 10^{-23} (m_\chi / \text{TeV})^{-3.2} \quad (k \neq 3), \quad (25)$$

$$|\lambda'_{i33}|_{\bar{p}} \lesssim 1 \times 10^{-22} (m_\chi / \text{TeV})^{-3.0}, \quad (26)$$

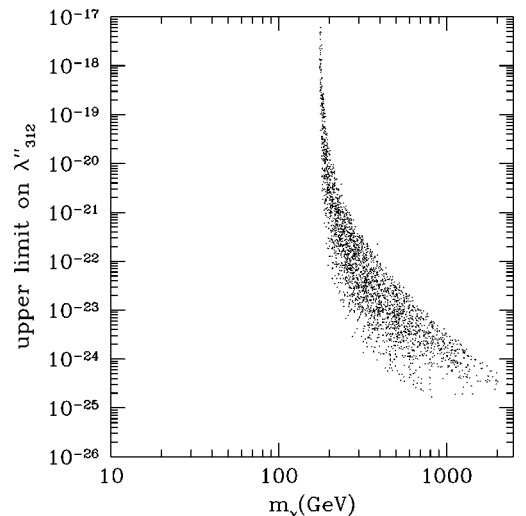


FIG. 3. Bounds on λ''_{312} from cosmic ray antiprotons as a function of the neutralino mass for 10^4 SUSY models. The threshold effect is clearly seen.

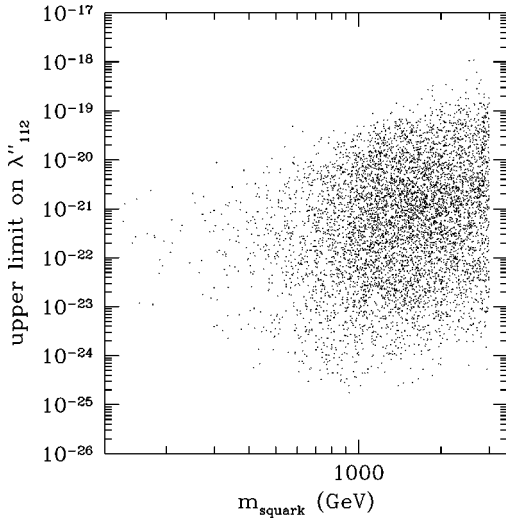


FIG. 4. Bounds on λ''_{112} from cosmic ray antiprotons as a function of the squark mass scale for 10^4 SUSY models.

$$|\lambda''_{ijk}|_{\bar{p}} \lesssim 3 \times 10^{-22} (m_{\chi}/\text{TeV})^{-2.7} \quad (i, k \neq 3), \quad (27)$$

$$|\lambda''_{ij3}|_{\bar{p}} \lesssim 3 \times 10^{-23} (m_{\chi}/\text{TeV})^{-2.7} \quad (i \neq 3). \quad (28)$$

For comparison, the most stringent laboratory constraints, those from proton decay [25], bound not $|\lambda'|$ and $|\lambda''|$ separately but their product to $|\lambda' \lambda''| \lesssim 10^{-24} (m_0/\text{TeV})^2$, where m_0 is the sfermion mass scale. These bounds are six orders of magnitude weaker than ours. On the other hand, because our analysis only applies to lifetimes longer than the age of the universe, our excluded region spans only 3 orders of magnitude. As mentioned in the Introduction, the remaining gap of 3 orders of magnitude may be filled by other cosmological considerations.

We finally comment on the dependence of our bounds on model parameters. In Fig. 4 we plot the dependence on the

squark mass scale m_0 . As expected, the bound is better for lighter squarks. Regarding the dependence on neutralino composition, in general the bounds are better in the gaugino region. In the Higgsino region, the bounds improve with heavier generations as the Yukawa couplings become larger. The dependence on other model parameters is negligible in comparison.

VIII. CONCLUSIONS

From observations of cosmic ray antiprotons we obtain strong constraints on each of the hadronic R -parity violating couplings $|\lambda'|$ and $|\lambda''|$ that appear in extensions of the minimal supersymmetric model. Our analysis applies strictly in cases where the neutralino lifetime is longer than the age of the universe, and enables us to exclude a range $\lambda_{\bar{p}} \leq |\lambda| \leq \lambda_0$, where $\lambda_{\bar{p}}$ is the upper limit from the antiproton flux and λ_0 is the validity boundary coming from the age of the universe. Using a large selection of model parameters, we find absolute upper limits $|\lambda'_{ijk}|_{\bar{p}} \lesssim 2 \times 10^{-18}$ and $|\lambda''_{ijk}|_{\bar{p}} \lesssim 10^{-18}$ when there is no top quark in the final state, and $|\lambda'_{i3k}|_{\bar{p}} \lesssim 4 \times 10^{-19}$ when there is. In virtually all models, we find that $\lambda_0 \gtrsim 10^3 \lambda_{\bar{p}}$. Our bounds lie many orders of magnitude below the laboratory constraints coming from proton decay, and apply to each R -parity violating coupling separately.

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